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Intelligent Control Strategies for Unmanned Aerial Systems

Ph. D. Work Plan

Submitted to

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Intelligent Control Strategies for Unmanned Aerial Systems.

1) A brief Introduction of Unmanned Aerial Vehicles (UAVs)

Developing an unmanned aerial vehicles control system has been one of the main points of concern by many countries all over the world; about 70 different countries have some sort of UAV technology. UAV expenditures reached more than US$ 3 billion and constituted a growth of more than 12% in 2010. Approximately 70% of global growth and market share is in the US. UAVs are used to gather information from the air in hostile areas. They can also be used in devastating areas where man support may not be available. These types of UAVs must be portable by ground and very reliable for recurrent use. With these types of uses by the military the UAVs designed are very costly and have very specific uses designed for each. The goal for the UAV design is to provide a cheaper alternative to these very costly military products. The UAV will be equipped HD camera with target recognition, weight under 55 lbs., and a GPS guided autopilot to fly desired flight path.
An unmanned aerial vehicle (UAV), known as a drone, is an aircraft without a human pilot.
Drone stands for Dynamic Remotely Operated Navigation Equipment.
Its flight is either controlled autonomously by computers or under the remote control of a piloton the ground.

The Tadiran Mastiff is a battlefield UAV built by Tadiran_Electronic_Industries, regarded by military historians as the world's first modern military drone.

Figure: First Drone by Israeli

The other perspective design, fabrication and control of Unmanned Aerial and Ground Vehicles (UAVs and UGVs) have become popular research topics during the last decade. Apart from various laboratories around the world, these vehicles have now been used in various military and civilian applications including surveillance, reconnaissance, search and rescue, and remote warfare. However, even today, all these operations require intensive human supervision and fully autonomous operation is still an interesting but challenging research problem. The situation becomes even more complicated when groups of UAV/UGVs are involved since computation, sensing, and communication are distributed over multiple agents and coordinating them to implement desirable collective behaviors is extremely difficult in general. Despite the difficulty, coordination and control of multiple UAVs and UGVs have many applications including automated highway systems, formation flight control and satellite clustering, mapping of unknown or partially known environments, and distributed manipulation. Given the numerous utilities of such

coordinated UAV/UGV teams, effective design and control of such groups is an area of intense current research.

Birth of UAVs :

- The earliest attempt at a powered unmanned aerial vehicle was A. M. Lows "Aerial Target" of 1916.
- After World War-I, including the first scale RPV, developed by the film star and model airplane enthusiast Reginald Denny in 1935.
- The birth of U.S. UAVs began in 1959 when United States Air Force officers, concerned about losing pilots over hostile territory.
- The August 1964,U.S. Navy initiated Americas highly classified UAVs into their first combat missions of the Vietnam War.
- The Israeli Tadiran Mastiff, which first flew in 1973, is seen as the first modern battlefield UAV, due to its data- link system and live video streaming.

Types of UAVs:

- MQ-9 Reaper, a hunter-killer surveillance UAV. (Also knows as killing machine) and they are usually deployed for military and special operation applications.
- DJI Phantom UAV for commercial and recreational aerial photography.(Also for educational and research purposes)

Technical Specifications:

While the overall goals, strategies and objectives have been stated, the specifications of the components will be determined as they are identified for their applicability in the project. The technical specifications are divided in the following in the engineering module on the basis of application and engineering involved. The modules are represented in the Table below:

Mechanical & Electrical Module	**Sensor Technology Module**
• Quad roto Frame • Landing Stand • 4 * Electrical Motor • 4 * Propellers • 2300 mAh Lipo Battery & charger Power distributed system	• IMU/3 Axis Digital Compass/Digital Pressure Sensor • On board camera • GPS • Telemetry
Embedded System & other Electronics Module	**Software Module**
• Flight Controller Using Arduino UNO board • An on-board processor using Raspberry Pi • ESC (Electronic speed control) • Transceiver (RF remote control)	• Matlab/Simulink • Cadsoft EAGLE, Fritzing • Aurduino IDE, Linux, Opencv • Python

Nowadays different types of drones evolved from the advancement in miniaturization of electronic components, such as sensors, microprocessors, batteries, and navigation systems. A wide variety of drones were used for military and civilian purposes. Drones range in size from vast fixed-wing unmanned air vehicle

(UAV) to smart dust (SD) which consists of many tiny micro-electro-mechanical systems including sensors or robots. In Fig. 1, the spectrum of different types of drones is presented:

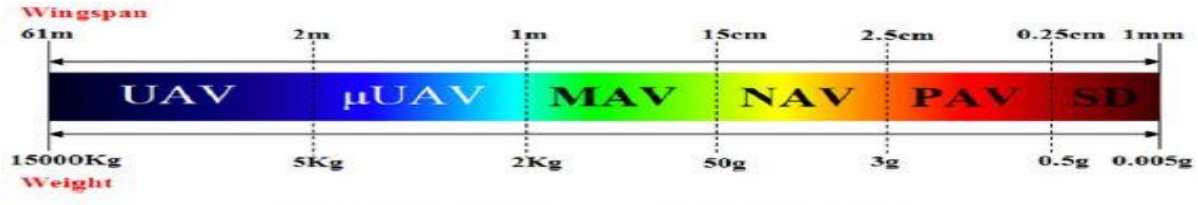


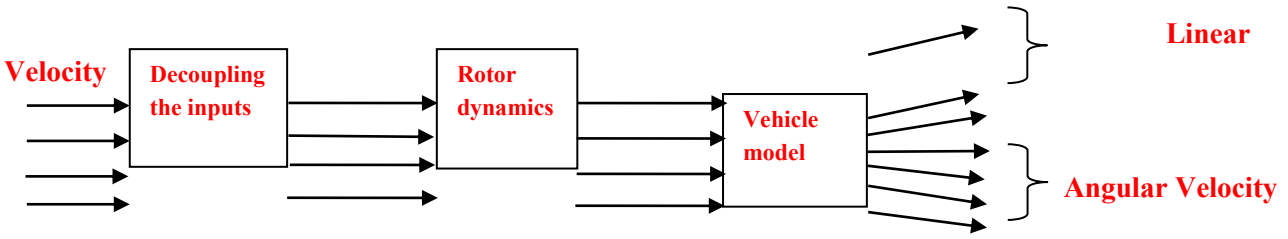
Fig. 1. Spectrum of drones from UAV to SD.

Basic Terminology

The details about the different methods used to control the position and the roll, yaw and pitch angle of the Unmanned Aerial vehicles (quadrotor). This investigation has been carried out using a full nonlinear Simulink model.

The three different methods are not described chronologically but logically, starting with the most mathematical approach and moving towards the most physically feasible approach.

In order to understand the common features of each approach, it is important to consider the following structure:



The methods differ in the following ways:

- Modelling the rotor dynamics
- Decoupling the inputs
- Designing the control law

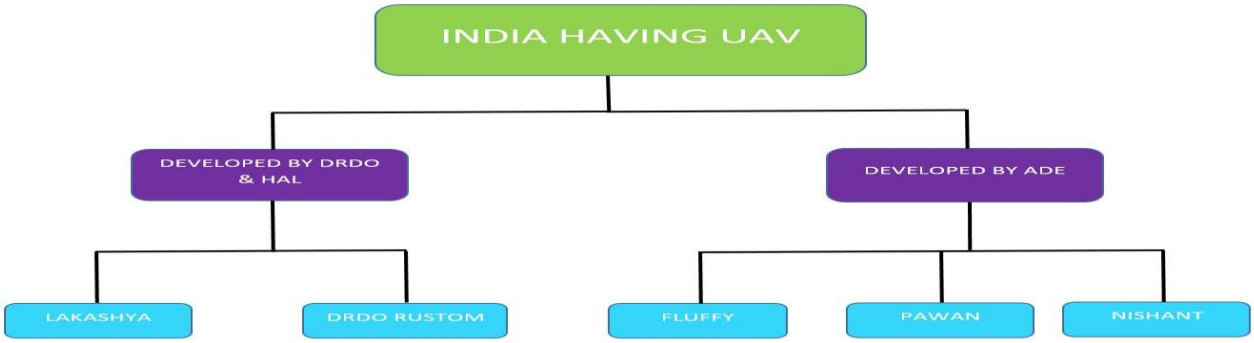
It can be foreseen that the mathematical approach will take into account all the different parameters and the following approaches will be simplifications of the first method making justified assumptions.

1. The first method uses a PID controller and feeds back the following variables:
   $x, \dot{x}, \ddot{x}, y, \dot{y}, \ddot{y}$, z, $\dot{z}$, $\ddot{z}$, $\dddot{z}$, ψ and $\dot{\psi}$.
2. The second method uses also a PID controller but feeds back φ, $\dot{\varphi}$, θ, $\dot{\theta}$ instead of $\ddot{x}, \dddot{x}, \ddot{y}, \dddot{y}$.
3. The third and last method feeds back the same variables as the second method but uses a simpler model for the rotor dynamics. Both PID and LQR techniques have been investigated with this model.

To design any acceptable model some trend has to be followed as:

- Starts with best guess
- Design a control system
- Test on hardware(Safely)
- Update model and control system

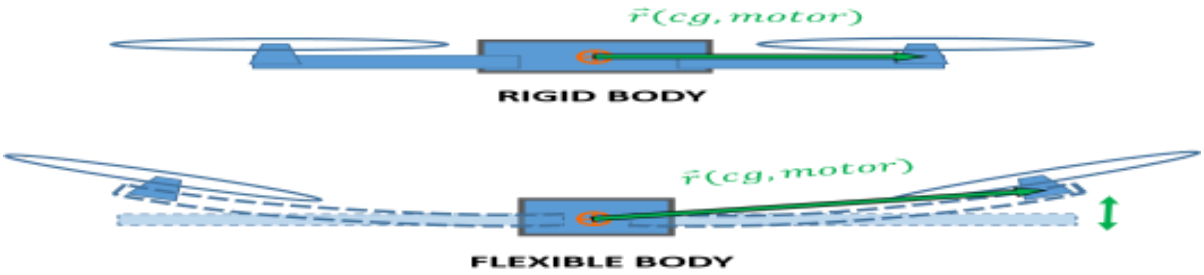
Drone Development in India:



DRDO chairman S Christopher said to the indian armed forces by 2020.

- Rustom drones are medium-altitude, Long range-endurance unmanned serial vehicles (UAVs). In 2017-2018 fiscal year 15000 crore UAv project were sanctioned.
- In 2018-2019 fiscal year 18,000 crore has allocated for Rustom-2.

Development of Vehicle dynamics



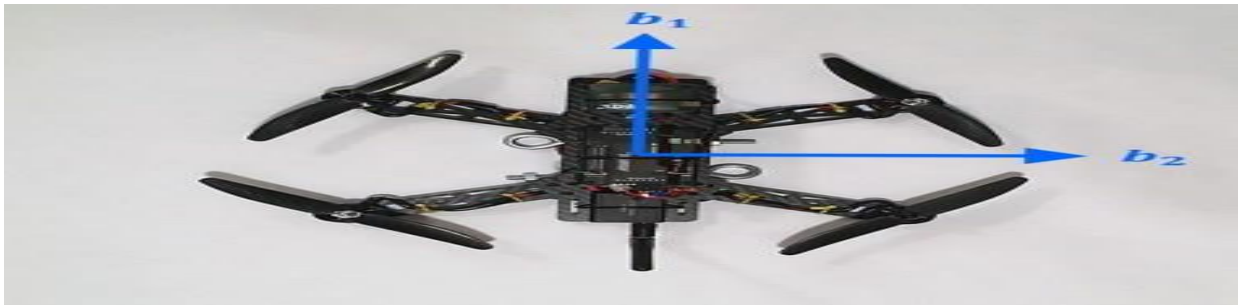
In a series on modelling and simulation of a quadcopter's vehicle dynamics the series will include:

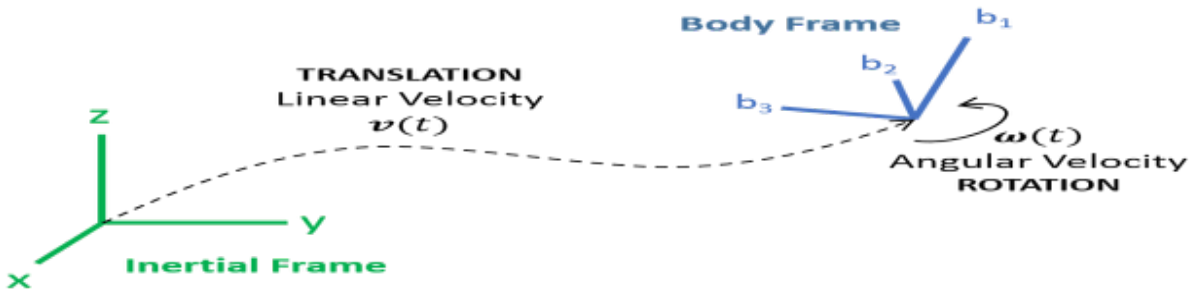
1. **Modeling Vehicle Dynamics – Euler Angles**
2. **Modeling Vehicle Dynamics – Quadcopter Equations of Motion**
3. **Modeling Vehicle Dynamics – 6DOF Nonlinear Simulation**

Euler Angles

1. **Inertial reference frame**
   This is fixed to the Earth and the coordinates could be based in cardinal directions (North, East), or arbitrary directions within a room floorplan. The main point is that it doesn't move (due to our flat-Earth assumption). For now, we will define the inertial frame with the coordinates (x, y, z).
2. **Body-fixed reference frame**
   Remember how we stated earlier that with a rigid body all components of the vehicle are fixed in relation to the CG? Well let's define a coordinate system with its origin at the GC, and now we have a convenient way to describe how far away the propellers are, and in what direction they face with respect to the CG. We will define the body-fixed reference frame with the coordinates (b_1, b_2, b_3)

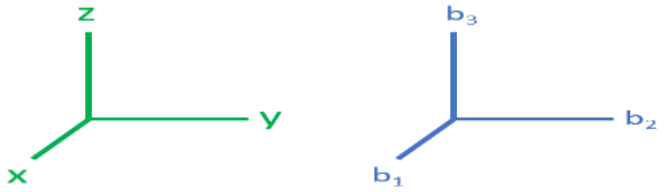
and align them with the structure such that b_1 and b_2 are aligned with symmetric axes of the body and b_3 is in the vertical direction (parallel to the propeller motor axes) as shown here:





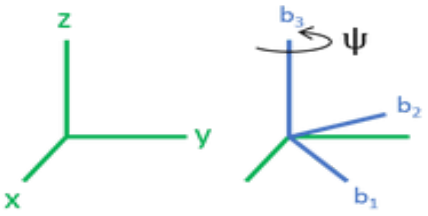
Euler Angles

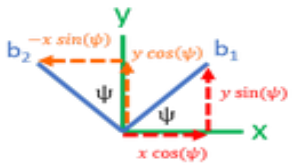
- Euler angles are that one can represent any final orientation of a reference frame via a set of 3 sequential rotations about specific axes.



$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

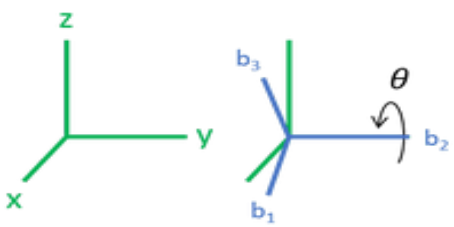
- When all 3 components are parallel to each other, it can be seen in the figure above that the transformation matrix is simply the identity matrix.
- Rotate the body frame about one of its axes by a specific amount
  We can describe the other body frame axes with trigonometry as a function of the inertial components and the angle of rotation.

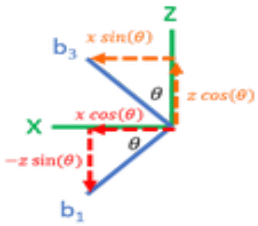




$$b_1 = x\cos(\psi) + y\sin(\psi)$$
$$b_2 = -x\sin(\psi) + y\cos(\psi)$$
$$b_3 = z$$

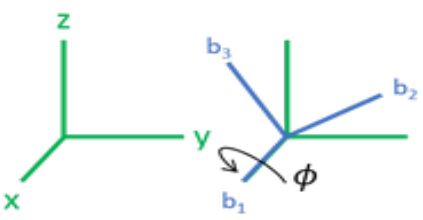
$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

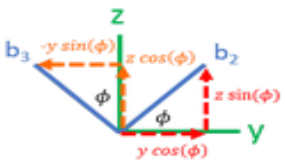




$$b_1 = x\cos(\theta) - z\sin(\theta)$$
$$b_2 = y$$
$$b_3 = x\sin(\theta) + z\cos(\theta)$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$





$$b_1 = x$$
$$b_2 = y\cos(\phi) + z\sin(\phi)$$
$$b_3 = -y\sin(\phi) + z\cos(\phi)$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \cos(\theta)\cos(\psi) & \cos(\theta)\sin(\psi) & -\sin(\theta) \\ -\cos(\phi)\sin(\psi) + \sin(\phi)\sin(\theta)\cos(\psi) & \cos(\phi)\cos(\psi) + \sin(\phi)\sin(\theta)\sin(\psi) & \sin(\phi)\cos(\theta) \\ \sin(\phi)\sin(\psi) + \cos(\phi)\sin(\theta)\cos(\psi) & -\sin(\phi)\cos(\psi) + \cos(\phi)\sin(\theta)\sin(\psi) & \cos(\phi)\cos(\theta) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad - \quad \mathbf{C}_n^b \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Now, if we want to perform a rotation in the reverse direction, from body-fixed frame coordinates to inertial coordinates, we need to use the inverse of the matrix. But instead of calculating the inverse of the matrix we can take advantage of the orthogonal property we identified earlier: that the transpose of a rotation matrix is equal to the inverse. Therefore, the reverse rotation is simply:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad - \quad \mathbf{C}_b^n \quad \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad - \quad [\mathbf{C}_n^b]^T \quad \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos(\theta)\cos(\psi) & -\cos(\phi)\sin(\psi) + \sin(\phi)\sin(\theta)\cos(\psi) & \sin(\phi)\sin(\psi) + \cos(\phi)\sin(\theta)\cos(\psi) \\ \cos(\theta)\sin(\psi) & \cos(\phi)\cos(\psi) + \sin(\phi)\sin(\theta)\sin(\psi) & -\sin(\phi)\cos(\psi) + \cos(\phi)\sin(\theta)\sin(\psi) \\ -\sin(\theta) & \sin(\phi)\cos(\theta) & \cos(\phi)\cos(\theta) \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Modeling Vehicle Dynamics – Quadcopter Equations of Motion

linear velocity

$$\mathbf{v}^b = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \text{longitudinal velocity} \\ \text{lateral velocity} \\ \text{normal velocity} \end{bmatrix}$$

angular velocity

$$\boldsymbol{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \text{roll rate} \\ \text{pitch rate} \\ \text{yaw rate} \end{bmatrix}$$

$$\text{Force} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

$$\text{Moment} = \begin{bmatrix} \mathcal{L} \\ \mathcal{M} \\ \mathcal{N} \end{bmatrix}$$

Euler angles

$$\boldsymbol{\Phi} = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \text{bank angle} \\ \text{pitch attitude} \\ \text{heading} \end{bmatrix}$$

$$\text{Navigation Coordinates} = \begin{bmatrix} x \\ y \\ h \end{bmatrix} = \begin{bmatrix} \text{longitudinal position} \\ \text{lateral position} \\ \text{height} \end{bmatrix}$$

Simultaneous Translation and Rotation – The Chain Rule

$$\mathbf{v}^b = \begin{bmatrix} u \\ v \\ w \end{bmatrix}^b = u\hat{b}_1 + v\hat{b}_2 + w\hat{b}_3$$

$$(\frac{d\mathbf{v}}{dt})_{\text{inertial}} = (\frac{du}{dt}\hat{b}_1 + \frac{dv}{dt}\hat{b}_2 + \frac{dw}{dt}\hat{b}_3) + (u\frac{d\hat{b}_1}{dt} + v\frac{d\hat{b}_2}{dt} + w\frac{d\hat{b}_3}{dt})$$

The components in the first set of parentheses represent the change in inertial velocity within the body frame coordinate system. The components in the second set of parentheses represent perceived velocity change due to the rotation of the coordinate frame. We can rewrite this equation as Coriolis' Theorem, where the frame rotation is represented by the angular velocity crossed with the velocity vector:

$$\dot{\mathbf{v}}_{\text{inertial}} = \dot{\mathbf{v}}^b + \boldsymbol{\omega}_{n}^{b} \times \mathbf{v}^b$$

In skew-symmetric cross-product matrix form:

$$\boldsymbol{\omega} \times \mathbf{v} = [\boldsymbol{\omega} \times]\mathbf{v} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \mathbf{v}$$

Newton's Second Law of Motion

Newton's 2nd Law which is commonly summarized as force (F) equals change in momentum (p), or for systems with constant mass, force equals mass (m) times acceleration (a) — the derivative of velocity (v):

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = m\frac{d\mathbf{v}}{dt} = m\mathbf{a}$$

This equation defines the change in linear momentum, however we can also express the rotational analogue. Crossing both sides of the equation with a position vector (r) from some origin O we get the rotational law of motion about the origin O. We can simplify the equation to moment (M) equals the change in angular momentum (H), or for systems with constant mass distribution, moment equals moment of inertia (I) times angular acceleration (Ω) — the derivative of angular velocity (ω).

$$\vec{\mathbf{r}} \times \mathbf{F} = \vec{\mathbf{r}} \times m\frac{d\mathbf{v}}{dt}$$

$$\mathbf{M} = \frac{d\mathbf{H}}{dt} = \mathbf{I}\frac{d\boldsymbol{\omega}}{dt} = \mathbf{I}\boldsymbol{\Omega}$$

Force, Mass, and Acceleration

Translation

$$\mathbf{F} = m\frac{d\mathbf{v}}{dt}$$

Inertial velocity in the body-fixed coordinate system will be expressed as: $\mathbf{v}^b = [u, v, w]^T$

Using the chain rule for a rotating body frame, the law of motion becomes:

$$\mathbf{F} = m(\dot{\mathbf{v}}^b + \boldsymbol{\omega}_n^b \times \mathbf{v}^b)$$

Rotation

$$M = \frac{d\mathbf{H}}{dt}$$

Angular velocity from inertial (n) to body-fixed (b) frame will be expressed as: $\boldsymbol{\omega}_n^b = [p, q, r]^T$

Using the chain rule for a rotating body frame, the rotational law of motion becomes:

M=Ib*Wnb + Wnb*Ib*Wnb

External Forces and Moments

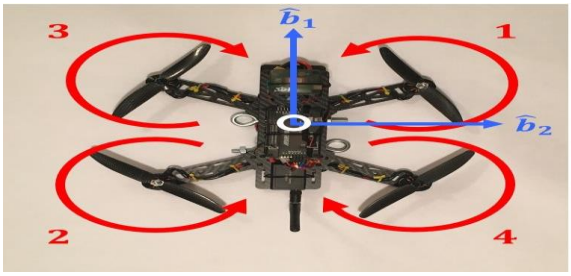
Propeller Thrust

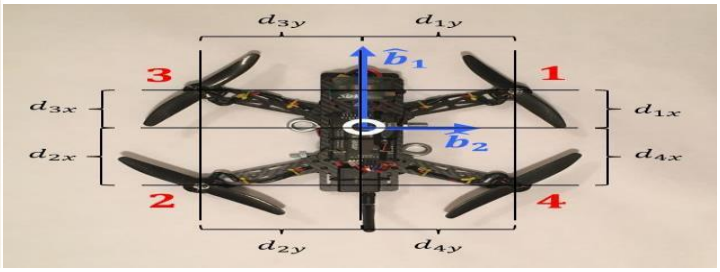
- The four quadcopter propellers provides a thrust force perpendicular to the propeller and a torque about the center of gravity of the vehicle.

- The thrust force is represented for each of the 4 propellers as $F_1, F_2, F_3, \text{and} F_4$. And all are aligned parallel with the vertical axis of the quadcopter, $\hat{b}_3$.

  The force vector within the body frame coordinate system can then be represented by:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -F_1 - F_2 - F_3 - F_4 \end{bmatrix}$$





The moments are represented with components L, M, N for rotations about the $\hat{b}_1, \hat{b}_2, \hat{b}_3$ axes, respectively. As a moment is measured by force times distance, we'll need the motor distances from the center of gravity, as shown in the image above. For pitch and roll, half the motors provide positive moment, and the other half provide a negative moment, depending on which side of the axis they are located.

$$L = F_1 d_{1y} - F_2 d_{2y} - F_3 d_{3y} + F_4 d_{4y}$$

$$M = -F_1 d_{1x} + F_2 d_{2x} - F_3 d_{3x} + F_4 d_{4x}$$

For yaw, the quadcopter takes advantage of its four rotating propellers. Half of the propellers are installed to rotate clockwise (#3 and #4) and the other half counter-clockwise (#1 and #2). Each propeller as it pushes against the air will also apply a torque about the cg of the quadcopter in the direction of its rotation as a function of its thrust, propeller radius, and distance from the cg. We will define this torque as a function $T(F, d_x, d_y)$, and can express the yaw moment of the vehicle as:

$$N = -T(F_1, d_{1x}, d_{1y}) - T(F_2, d_{2x}, d_{2y}) + T(F_3, d_{3x}, d_{3y}) + T(F_4, d_{4x}, d_{4y})$$

Gravity Force in Body Coordinates

Gravity always acts towards the center of the Earth, and is expressed in the inertial frame as:

$$\mathbf{F}_{grav}^{n} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}$$

Where g = 9.81 m/s^2, the gravitational constant. Remember that our z-inertial coordinate is in the Down direction, so gravity is a positive acceleration.

But all of our other forces are defined within the body frame of the vehicle. To include gravity in our equations of motion we must convert it into body frame components as well. Using our Euler angle transformation matrix from inertial to body frame, $\mathbf{C}_n^b$, this is easy:

$$\mathbf{F}_{grav}^{b} = \mathbf{C}_n^b \mathbf{F}_{grav}^{n} = \begin{bmatrix} c_\theta c_\psi & c_\theta s_\psi & -s_\theta \\ -c_\phi s_\psi + s_\phi s_\theta c_\psi & c_\phi c_\psi + s_\phi s_\theta s_\psi & s_\phi c_\theta \\ s_\phi s_\psi + c_\phi s_\theta c_\psi & -s_\phi c_\psi + c_\phi s_\theta s_\psi & c_\phi c_\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}$$

$$\mathbf{F}_{grav}^{b} = \begin{bmatrix} -mg\sin(\theta) \\ mg\sin(\phi)\cos(\theta) \\ mg\cos(\phi)\cos(\theta) \end{bmatrix}$$

Mass and Moment of Inertia

The moment of inertia is defined in physics for scalars as:

$$I = mr^2$$

The Moment of Inertia Matrix (I)

A more general representation where the mass is integrated over the entire body of the object is:

$$\mathbf{I} = \int_{body} \mathbf{r}^2 dm$$

To represent this in matrix form, we will assume $\mathbf{r}$ is some coordinate with components $[x, y, z]$ in relation to the reference frame origin. Then using the cross-product matrix form of $[\mathbf{r}\times]$ we can evaluate:

$$\mathbf{I} = \int_{body} \mathbf{r}^2 dm = \int_{body} [\mathbf{r} \times \mathbf{r} \times dm]$$

$$\mathbf{I} = \int_{body} \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix} \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix} dm$$

$$\mathbf{I} = \begin{bmatrix} \int (y^2 + z^2) dm & -\int (xy) dm & -\int (xz) dm \\ -\int (xy) dm & \int (x^2 + z^2) dm & -\int (yz) dm \\ -\int (xz) dm & -\int (yz) dm & \int (x^2 + y^2) dm \end{bmatrix}$$

$$\mathbf{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix}$$

$$I_{xx} = \sum_i (y_i^2 + z_i^2) m_i$$

Symmetry

$$I_{xy} = \sum_i x_i y_i m_i$$

$$= -\left(\sum_i^{\{x_i \geq 0\}} x_i y_i m_i\right) + \sum_i^{\{x_i \geq 0\}} x_i y_i m_i = 0$$

If the quadcopter is built so it is symmetric about both the x and y axes, then the inertia matrix would become:

$$\mathbf{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$$

Acceleration

Linear Acceleration

We have already learned that we must use Coriolis' Theorem to represent the inertial velocity derivative in the rotating body frame. And we came up with the formula:

$$\dot{\mathbf{v}}_{\text{inertial}} = \dot{\mathbf{v}}^b + \boldsymbol{\omega}_n^b \times \mathbf{v}^b = \dot{\mathbf{v}}^b + \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \mathbf{v}$$

If we plug in our nomenclature for $\mathbf{v}^b = [u, v, w]^T$ and $\boldsymbol{\omega}^b = [p, q, r]^T$, we get:

$$\dot{\mathbf{v}}^b = \dot{\mathbf{v}}^b + \boldsymbol{\omega}_n^b \times \mathbf{v}^b = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}^b + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}^b = \begin{bmatrix} \dot{u} + qw - rv \\ \dot{v} + ru - pw \\ \dot{w} + pv - qu \end{bmatrix}$$

Translational Motion

We have now derived representations for all components of our system's force, mass, and acceleration in translation. Plugging these into Newton's formula provides us with our first set of equations of motion.

$$\mathbf{F} = m\mathbf{a}$$

$$\mathbf{F}_{prop} + \mathbf{F}_{grav} = m\dot{\mathbf{v}}^b_{inertial}$$

$$\begin{bmatrix} -mg\sin(\theta) \\ mg\sin(\phi)\cos(\theta) \\ -F_1 - F_2 - F_3 - F_4 + mg\cos(\phi)\cos(\theta) \end{bmatrix} = m \begin{bmatrix} \dot{u} + qw - rv \\ \dot{v} + ru - pw \\ \dot{w} + pv - qu \end{bmatrix}$$

Angular Acceleration and Rotational Motion

We follow a similar procedure to solve for the angular acceleration and rotational law of motion. Using Coriolis' Theorem again for the time derivative of angular velocity, we can evaluate the rotational motion formula as follows:

$$\mathbf{M} = \mathbf{I}^b\dot{\boldsymbol{\omega}}_n^b + \boldsymbol{\omega}_n^b \times \mathbf{I}^b\boldsymbol{\omega}_n^b$$

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

But if we assume our quadcopter is symmetric about both the x and y axes of the body frame, then the products of inertia all go to zero and this becomes:

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ I_{zz}\dot{r} \end{bmatrix} + \begin{bmatrix} -I_{yy}qr + I_{zz}qr \\ I_{xx}pr - I_{zz}pr \\ -I_{xx}pq + I_{yy}pq \end{bmatrix}$$

Additional Coordinate Frame Transformations

Angular Velocity vs. Euler Angle Rates

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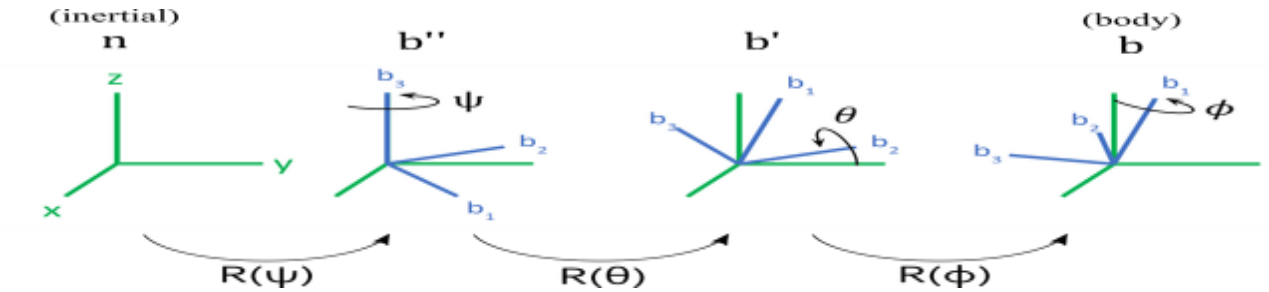


(Sequence of Euler Angle Rotations (Body 3-2-1) from inertial to body-fixed reference frames, with intermediate reference frames b" and b')

The relationship between measured gyro rates and Euler angle rates can be expressed in scalar form multiplied by unit vectors as:

$$p(\hat{b}_1) + q(\hat{b}_2) + r(\hat{b}_3) = \dot{\psi}(\hat{b}_3'') + \dot{\theta}(\hat{b}_2') + \dot{\phi}(\hat{b}_1)$$

If we express it in matrix form however, we can take advantage of our rotation matrices to handle the disparate reference frames:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & s_\phi \\ 0 & -s_\phi & c_\phi \end{bmatrix} \begin{bmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & s_\phi \\ 0 & -s_\phi & c_\phi \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix}$$

To make things a little easier to read and fit on the page, I'm going to use a shorthand for the trigonometric functions: $c_\theta = \cos(\theta)$ and $s_\theta = \sin(\theta)$. The above expression can be simplified by multiplying the matrices.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & s_\phi \\ 0 & -s_\phi & c_\phi \end{bmatrix} \begin{bmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & s_\phi \\ 0 & -s_\phi & c_\phi \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} -\dot{\psi}s_\theta \\ \dot{\psi}c_\theta s_\phi \\ \dot{\psi}c_\phi c_\theta \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\theta}c_\phi \\ -\dot{\theta}s_\phi \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{aligned} p &= \dot{\phi} - \dot{\psi}\sin\theta \\ q &= \dot{\theta}\cos\phi + \dot{\psi}\cos\theta\sin\phi \\ r &= \dot{\psi}\cos\phi\cos\theta - \dot{\theta}\sin\phi \end{aligned}$$

These equations can also be rewritten for the Euler angle derivatives:

$$\begin{aligned} \dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta \\ \dot{\theta} &= q\cos\phi - r\sin\phi \\ \dot{\psi} &= (q\sin\phi + r\cos\phi)\sec\theta \end{aligned}$$

The Navigation Coordinates

To determine the motion of the vehicle within our navigation coordinate frame, we simply transform our body frame velocity states with our Euler angle transformation matrix. Also we define our height variable, h, as the negative of our North-East-Down inertial frame to get a North-East-Up navigation frame. So below I've made the substitution $z = -h$.

$$\begin{bmatrix} \dot{x}^E \\ \dot{y}^E \\ -\dot{h}^E \end{bmatrix} = \mathbf{C}_b^n \begin{bmatrix} u \\ v \\ w \end{bmatrix}^b = \begin{bmatrix} c_\theta c_\psi & -c_\theta s_\psi + s_\phi s_\theta c_\psi & s_\phi s_\psi + c_\phi s_\theta c_\psi \\ c_\theta s_\psi & c_\phi c_\psi + s_\phi s_\theta s_\psi & -s_\phi c_\psi + c_\phi s_\theta s_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}^b$$

12-Equations of Motion The Quadcopter :

Finally we have collected all the pieces to fully describe the motion of the quadcopter. Collecting all of the equations into one set and rearranging them we arrive at:

$$\begin{aligned}
\dot{u} &= -g\sin(\theta) + rv - qw \\
\dot{v} &= g\sin(\phi)\cos(\theta) - ru + pw \\
\dot{w} &= \tfrac{1}{m}(-F_z) + g\cos(\phi)\cos(\theta) + qu - pv \\
\dot{p} &= \tfrac{1}{I_{xx}}(L + (I_{yy} - I_{zz})qr) \\
\dot{q} &= \tfrac{1}{I_{yy}}(M + (I_{zz} - I_{xx})pr) \\
\dot{r} &= \tfrac{1}{I_{zz}}(N + (I_{xx} - I_{yy})pq) \\
\dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\psi} &= (q\sin\phi + r\cos\phi)\sec\theta \\
\dot{x}^E &= c_\theta c_\psi u^b + (-c_\phi s_\psi + s_\phi s_\theta c_\psi)v^b + (s_\phi s_\psi + c_\phi s_\theta c_\psi)w^b \\
\dot{y}^E &= c_\theta s_\psi u^b + (c_\phi c_\psi + s_\phi s_\theta s_\psi)v^b + (-s_\phi c_\psi + c_\phi s_\theta s_\psi)w^b \\
\dot{h}^E &= -1 * (-s_\theta u^b + s_\phi c_\theta v^b + c_\phi c_\theta w^b)
\end{aligned}$$

where

$$\begin{aligned}
F_z &= F_1 + F_2 + F_3 + F_4 \\
L &= F_1 d_{1y} - F_2 d_{2y} - F_3 d_{3y} + F_4 d_{4y} \\
M &= F_1 d_{1x} - F_2 d_{2x} + F_3 d_{3x} - F_4 d_{4x} \\
N &= -T(F_1, d_{1x}, d_{1y}) - T(F_2, d_{2x}, d_{2y}) + T(F_3, d_{3x}, d_{3y}) + T(F_4, d_{4x}, d_{4y})
\end{aligned}$$

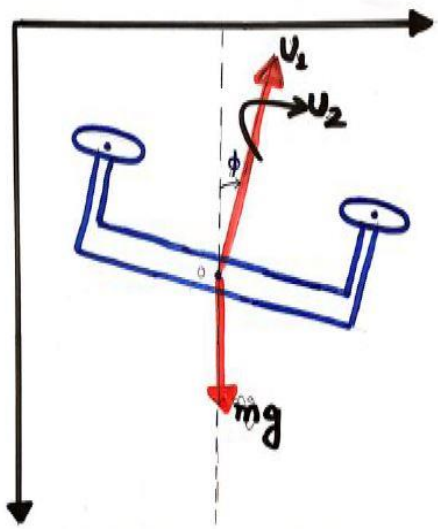
and h^E is positive in the up direction.

Commom Simulation Workflow for UAVs:

1. **Representing a UAV with a kinematic model**.
   - UAV Guidance Model Block
2. **Controlling and tunning the model using a waypoint following algorithm.**
   - Waypoint Follower Block
3. **Visualizing the flight behaviour and analysing the flight data.**
   - UAV Animation Block

Quadcopter UAV Trajectory and Control Design 3 dof's

U_1 = Force From Propellers
U_2= Moment
m = Mass
ϕ = Roll angle
$I_x x$ = Moment of Inertia



Equation of motion:

Non-linear equations

$$\begin{cases} \textit{linear accelerartion} : \ddot{z} = g - \frac{U_1}{m} * \cos\phi \\ \textit{linear accelerartion} : \ddot{y} = \frac{U_1}{m} * \sin\phi \\ \textit{Angular accelerartion} : \ddot{\phi} = \frac{U_2}{I_{xx}} \end{cases}$$

To linearize around the hover point We consider:

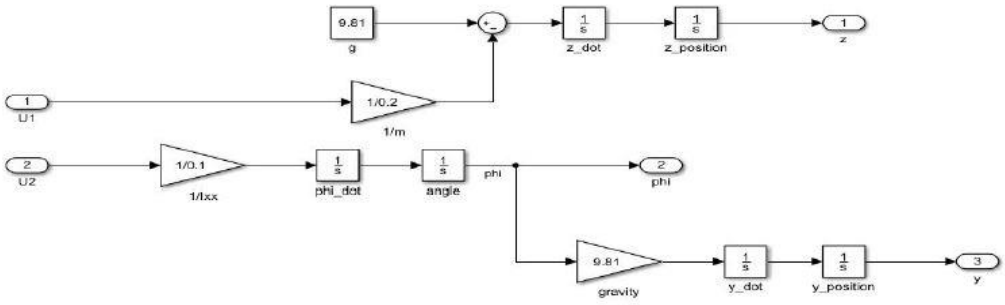
$U_2 = 0$

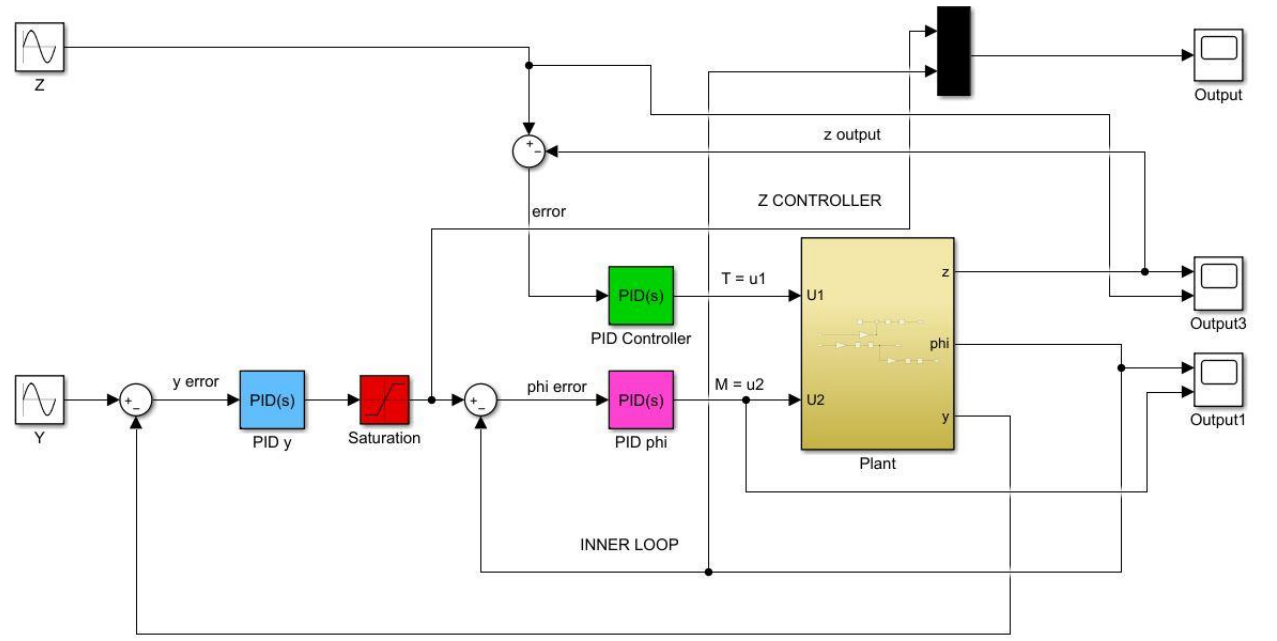
$U_1 = m * g$ because $\ddot{z}$ and $\ddot{y}$ are 0

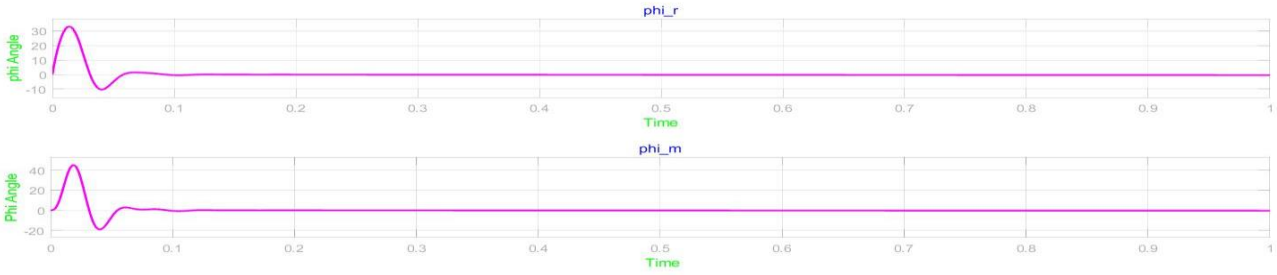
$\phi = 0$

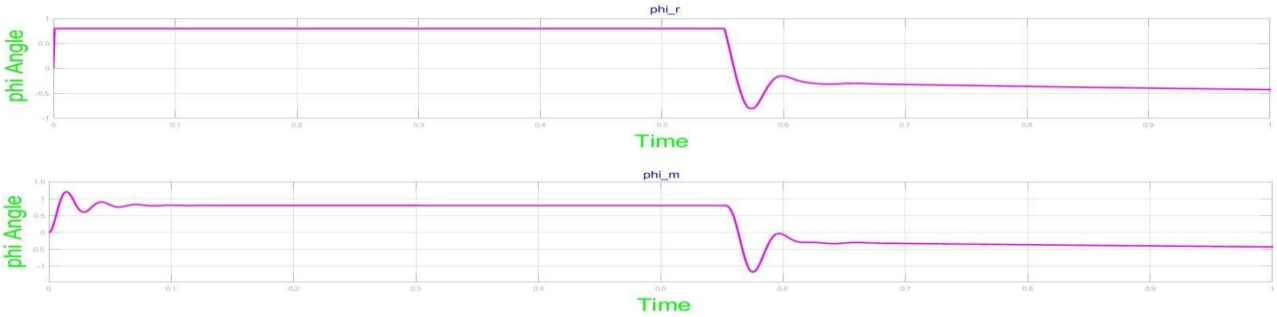
So from Non linear quation we can write:

$$\textbf{Linear-Equation} \begin{cases} \ddot{z} = g - \frac{U_1}{m} * \cos(0 + \Delta\phi) = g - \frac{U_1}{m} \\ \ddot{y} = \frac{U_1}{m} * \sin\phi = \frac{m*g}{m} * \phi = g * \phi \\ \ddot{\phi} = \frac{U_2}{I_{xx}} \end{cases}$$









4) Objectives of the research and proposed hypothesis.

1. Study of various Control Strategies techniques for Unmanned Aerial Vehicles (UAVs).
2. Study of different Controller design techniques and control Laws.
3. Implementation of Model-based nonlinear controller, linear flight control system, learning-based flight controller for UAVs.
4. Implementation of Observer based robust control strategies for UAVs.

5. Implementation of control algorithms for Motion planning (also called Path planning) of UAVs i.e. determining the optimal path for the vehicle in accordance with specific objectives and constraints such as obstacles go.
6. Implementation of control algorithms for Trajectory Generation i.e. designed for optimal control and maneuverability to follow a particular route or to go from one place to another.
7. Implementation of control algorithms for Task Allocation and Scheduling i.e. set the optimal distribution of tasks between a group of agents, with time constraints and equipment limitations.
8. Numerical simulation and Experimental validation.
9. Investigation and real time implementation.
   If Time Permits then next proposed work will be:
10. Try to implement the hardware.
11. Implementation of Multi-drones-cooperation, like- Coordinate flight control, Cooperative mission planning and decision-making and Path planning.

6) Importance of the study and Challenges:

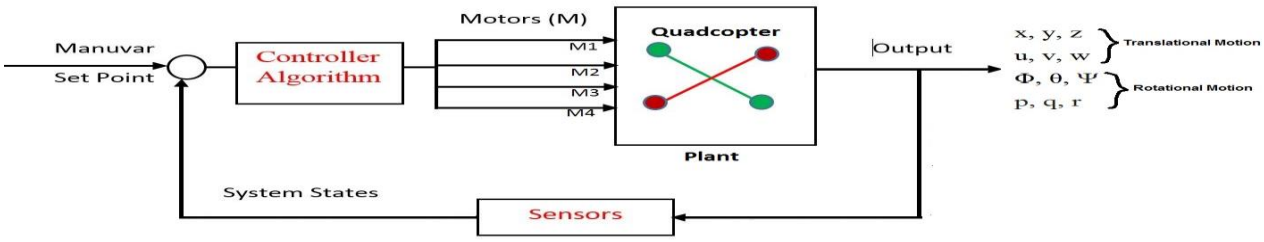
UAV or drones first came to application as small toys, or school/university projects and then no sooner began to garner widespread attention- used in big-budget movies, photography of high profile sports, agricultural use to rectify lands and detect levels of pesticides as well as other components like nitrogen in plants, search and rescue, land mapping, military.etc. The commercial as well as private use of drones is enlarging.

The main point is that with growing progress in technology, drones too are coming in different shapes, sizes and configuration (UAV, hexacopters, etc.) for better load and yaw stability. Moreover, extended components like camera, water- resistant components or GPS tracker make it easy in missions of combating, surveillance and especially search and rescue.

After 10 years, the market for commercial drones will reach $1.7 billion. Each year, $6.4 billion is being spent developing drone technology. The drones are even providing new job opportunities. 70,000 new drone-related jobs are projected within the next three years in the USA alone. 100,000 new jobs are expected to 10 years. Moreover, schools are offering drone degrees & programs in order to provide a trained workforce capable of meeting this demand. This may also prove that there is no need for people to fear about losing their jobs because of replacement by robots or drones. But there are also some concerns like all the new leading technologies. It is important to plan appropriately to achieve a productive outcome. Privacy among being the major concern in warfare, could be used as a means of spying which is mere exploitation and negative use of UAV technology.

Since the advantages of UAV technology are more than its demerits (are very well rectifiable), then according to drone experts, drones will be “in trend” within the next 10 to 20 years.

There is a wide scope that with its extending use in almost every field and with greater powerful components, drones will surely come into full time existence. Hence UAV will very soon start taking over larger roles in a variety of research.



7) Proposed work plan- with a tentative chapter scheme

- Chapter 1: Introduction and Literature Survey
- Chapter 2: Investigation of Model-based nonlinear control law
- Chapter 3: Investigation of Linear flight control system
- Chapter 4: Investigation of Learning-based flight control law
- Chapter 5: Investigation of Path planning, Mission planning and Multi drones cooperation
- Chapter 6: Investigation of various control strategies for a different type of UAVs
- Chapter 7: Comparative study and stability analysis
- Chapter 8: Conclusion/Future work

8) Year wise plan of work and targets to be achieved

	July-December	**December-June**
2019	• Literature Survey of UAVs. • Study of various Control Strategies techniques like: PID, SMC, ADRC for Unmanned Aerial Vehicles (UAVs).	
2020	• Implementation of control algorithms for Motion planning. • Implementation of control algorithms for Trajectory Generation. • Implementation of control algorithms for Task Allocation and Scheduling.	• Simulation and Investigation of control strategies for Unmanned Aerial Vehicles. • A comparative study, stability analysis, accuracy, robustness and efficiency of proposed control strategies.
2021	**Preparation of Thesis on Intelligent Control Strategies of Unmanned Aerial Vehicle.**	

9) Expected outcome

1. Simulation of different Control strategies in Literature.

2. Implementation of Model based control strategies like: Feedback Linearization, Adaptive control for Unmanned Aerial Vehicles.
3. Implementation of Linear Flight control system like: Proportional-Integral-Derivative, H, Gain Scheduling, Linear-Quadratic Regulator for Unmanned Aerial Vehicles.
4. Implementation of Learning based flight control like: Fuzzy Logic, Neural networks for Unmanned Aerial Vehicles.
5. Comparison of robustness and effectiveness of the proposed control strategy.

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9. An overview of recent progress in the study of distributed multi-agent coordination Cao et al. (2015), IEEE Transactions on Industrial Informatics.
10. Handbook of Unmanned Aerial Vehicles, Kimon P. Valavanis George J. Vachtsevanos Editors, Springer Reference

Most ten (10) cited papers relating to UVS:

1. An overview of recent progress in the study of distributed multi-agent coordination
   Cao et al. (2015), IEEE Transactions on Industrial Informatics
2. Unmanned aerial systems for photogrammetry and remote sensing: a review
   Colomina and Molina (2014), ISPRS Journal of Photogrammetry and Remote Sensing
3. Flexible high power-per-weight perovskite solar cells with chromium oxide-metal contacts for improved stability in air
   Kaltenbrunner et al. (2015), Nature Materials
4. Lightweight unmanned aerial vehicles will revolutionize spatial ecology

Anderson and Gaston (2013), Frontiers in Ecology and the Environment

5. Flying ad-hoc networks (FANETs): a survey
   Bekmezci et al. (2013), Ad Hoc Networks
6. Comparison of parallel genetic algorithm and particle swarm optimization for real-time UAV path planning
   Roberge et al. (2013), IEEE Transactions on Industrial Informatics
7. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments
   Mancini et al. (2013), Remote Sensing
8. A review of space robotics technologies for on-orbit servicing
   Flores-Abad et al. (2014), Progress in Aerospace Sciences
9. High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision
   Dandois and Ellis (2013), Remote Sensing of Environment
10. Mobile 3D mapping for surveying earthwork projects using an unmanned aerial vehicle (UAV) system
    Seibert and Teizer (2014), Automation in Construction

Journals that have published the most papers relating to UVS:

- Journal of Intelligent & Robotic Systems
- Sensors
- Remote Sensing
- Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering
- International Journal of Remote Sensing
- Aerospace Science and Technology
- International Journal of Advanced Robotic Systems
- Journal of Guidance, Control, and Dynamics
- IEEE Transactions on Control Systems Technology
- IEEE Transactions on Aerospace and Electronic Systems
- Journal of Aerospace Information Systems
- Aircraft Engineering and Aerospace Technology
- Journal of Aircraft
- Mathematical Problems in Engineering
- Journal of Field Robotics
- Robotics and Autonomous Systems
- Journal of Aerospace Engineering (ASCE)
- PLoS ONE
- Chinese Journal of Aeronautics
- ISPRS Journal of Photogrammetry and Remote Sensing

Resources

- Examples http://www.mathworks.com
- Videos
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- Book Program
- Hardware support packages
- Webinars

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